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Agile Modeling of Component Connections for Simulation and Design of Complex Vehicle Structures

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Overview

- Background and Motivation
- Methods for joining topology optimization
- Numerical Results
- Conclusions

Motivation

- How to Join the components ?

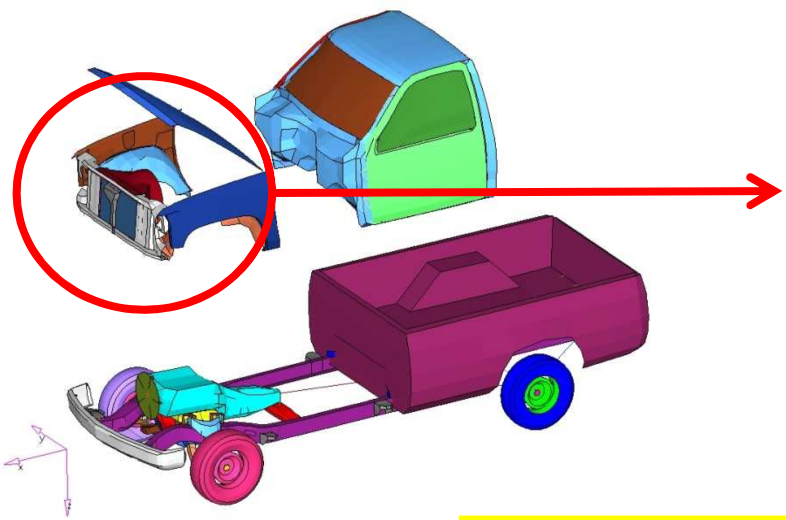
  "… 4,608 spot welds on the [vehicle], which had just 1.4 m of laser welding… "

  By Dr. Klaus Loeffler, Director, Joining Processes, Volkswagen AG,

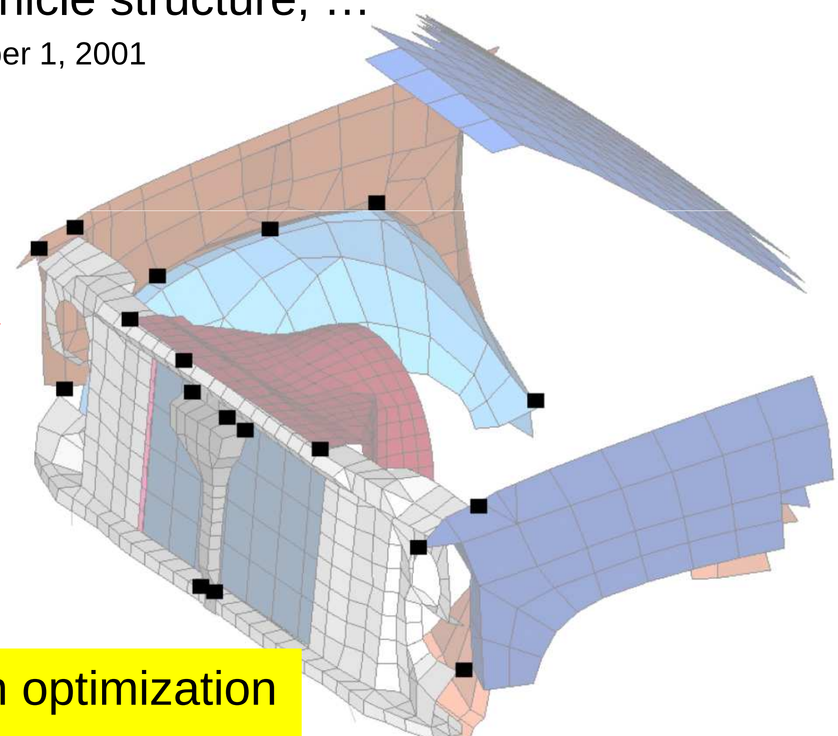
  -- Automotive Design and Production, May 4, 2007

  "… more than 4,000 spot welds connect some 300 body panels on a typical mid-sized car to form the basic vehicle structure, …"

  By Louise Elliott, Regional Editor -- Design News, October 1, 2001

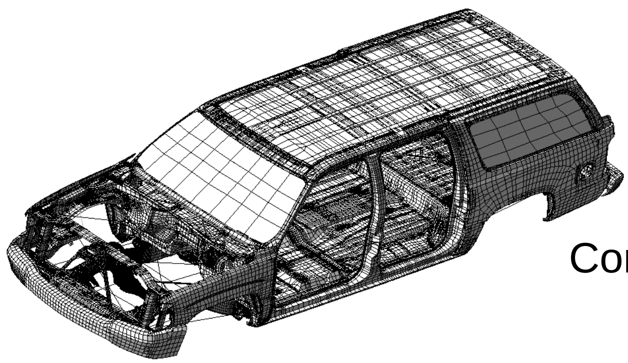


Hard to determine joining locations



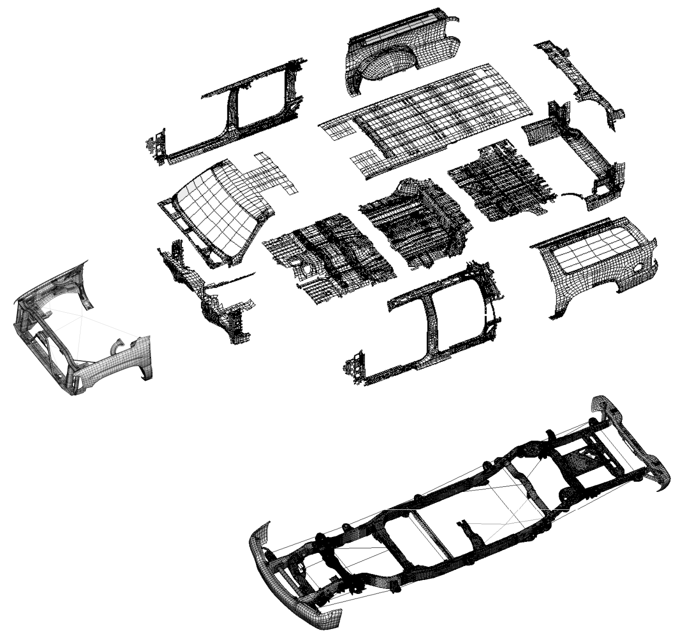
Joining design optimization
Among components

Reduced order modeling



Divide and Conquer

Component Mode Synthesis
(CMS)

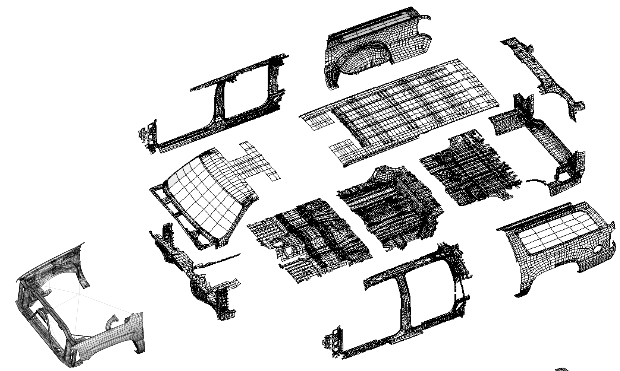


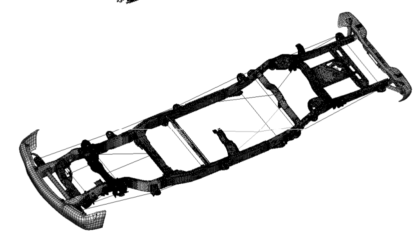
- Divide structure into substructures (components)

- Use component mode synthesis (CMS) to generate reduced-order models (ROMs)
    1. ROM size << FEM size due to modal analysis for each component
    2. **ROM retains physical (FE) DOF at interface between components**

Joining modeling & design approach

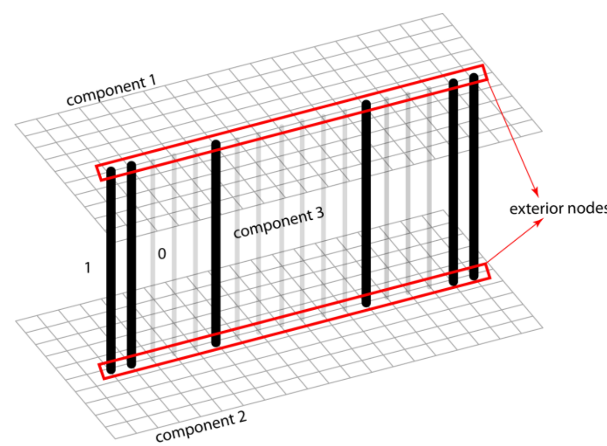
- Divide structure into components such that interface between components includes potential joining locations
  - **ROM retains physical (FE) DOF for potential joining locations**





- Treat connections between two components as joining design variables (joining is treated like a “third component”)
  - Continuous variable: e.g., spring with varying stiffness
  - Discrete variable: connection is on or off

- Perform joining design optimization to achieve system-level performance requirements



Previous joining design research

- System level topology optimization in full order model :
  Extension of the component topology optimization (Bensøe and Kikuchi , (1988))

  - Chirehdast and Jian (1996)
    - Optimal design of spot-weld and adhesive bond patterns for static compliance
  - Chickermane and Gea (1997)
    - Multi-component structural systems for optimal layout topology and joint locations for static compliance

- Interface design via ROM
  - Jiang , Cui, Ma, and Hadi (2005)
    - Optimal mount position and mount properties via size optimization

- Objectives of this work:

1. Use ROM to perform fast system-level analysis and joining design optimization
2. Optimize joining for static and dynamic structural response objectives while constraining maximum joining area

Structural Topology Optimization

Design Domain Modeling

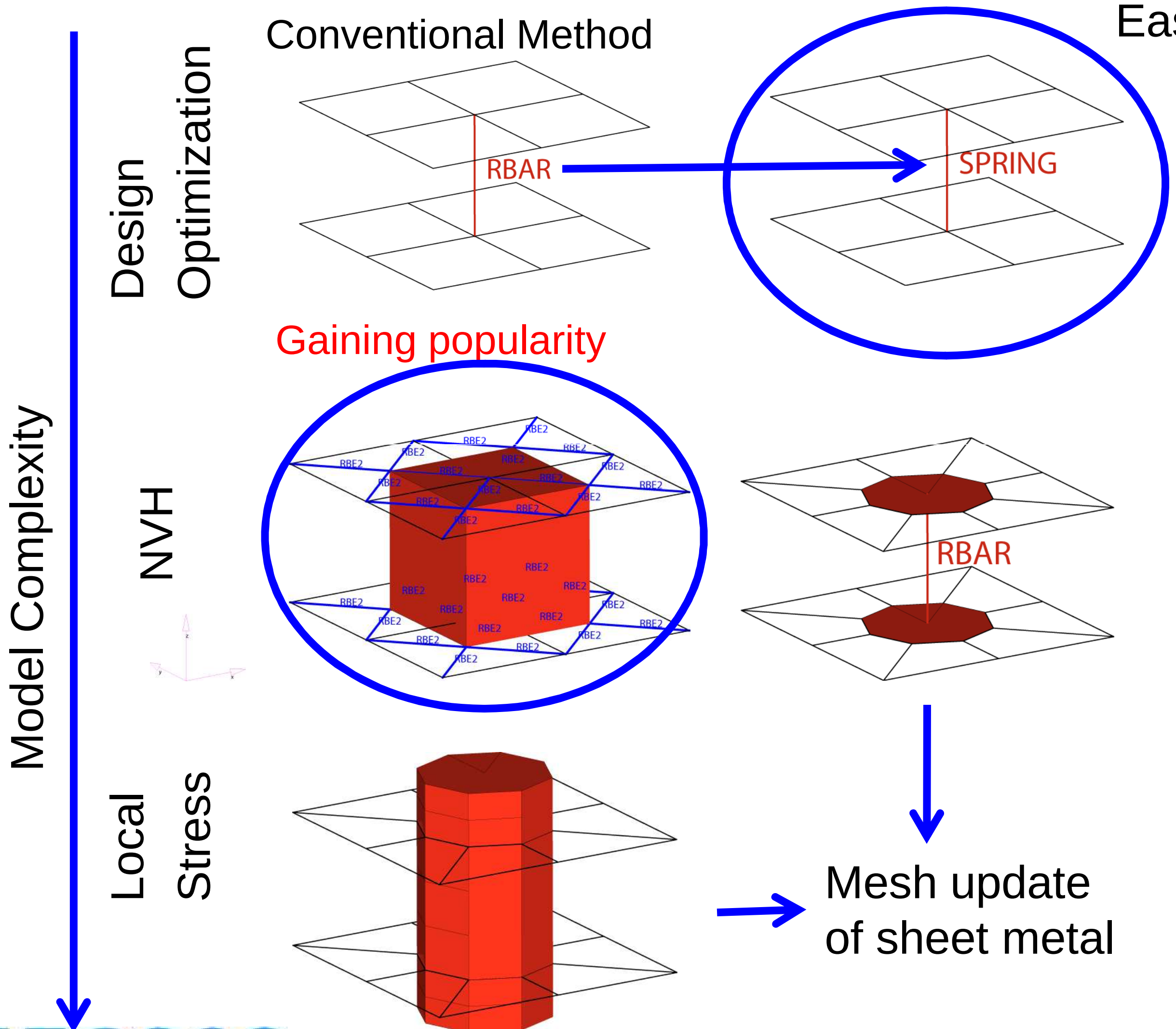
- **Homogenization Method** – Bensøe and Kikuchi
  - ✓ Relatively stable, but slow
- **SIMP** (Solid Isotropic Material with Penalization) – Bensøe and Sigmund
  - ✓ Relatively fast, small number of design variables

Optimization Methods

- **OC (Optimality Criteria)** – Karush, Khun and Tucker
  - ✓ KKT Condition and Nonlinear Solver
- **MOC (Modified OC)** – Ma, Kikuchi, and Hagiwara ('93)
  - ✓ Shifted Lagrangian in OC
- **MMA (Method of Moving Asymptotes)** – K. Svanberg ('87)
  - ✓ Convex Linearization with Asymptotes of Objective and Constraints

Joining modeling in FEA

- Dominant Joining (Spot-Welding) modeling



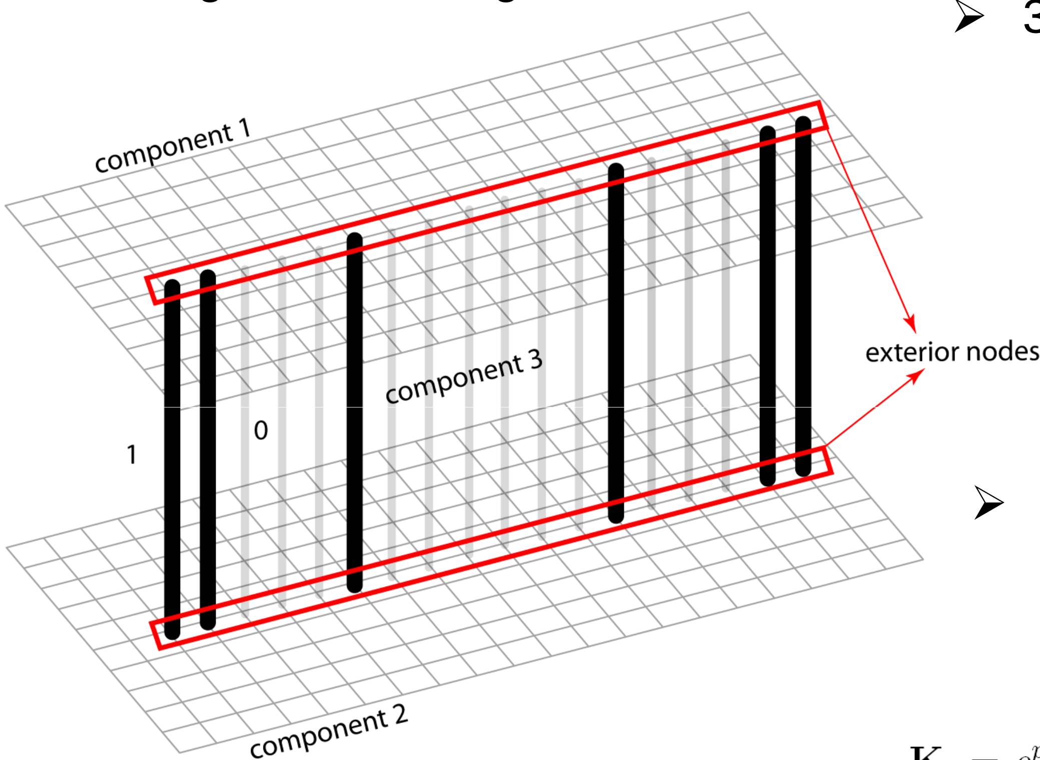
Ease of automatic updating

$$K_s = \begin{bmatrix} k_s & -k_s \\ -k_s & k_s \end{bmatrix}$$

$$k_s = k_y \, \mathrm{Diag}([\mu_k \;\; 1 \;\; \mu_k])$$

Joining modeling in current study

- Topology optimization for joining (Design domain modeling + Optimizer) in ROM Leading to "0-1" design



➢ 3D Spring with continuous variables

$$\mathbf{K_s} = \begin{bmatrix} \mathbf{k_s} & -\mathbf{k_s} \\ -\mathbf{k_s} & \mathbf{k_s} \end{bmatrix}$$

$$\mathbf{k_s} = \mathbf{k_y}\,\mathbf{Diag}([\alpha_\mathbf{k}\ \mathbf{1}\ \alpha_\mathbf{k}])$$

➢ Design domain modeling

✓ SIMP (Solid Isotropic Material with Penalization)

$$\mathbf{K}_e = \rho_e^p \begin{bmatrix} \mathbf{k}_s & -\mathbf{k}_s \\ -\mathbf{k}_s & \mathbf{k}_s \end{bmatrix} = \rho_e^p \mathbf{K}_s^0 \qquad \sum_{e=1}^{n_{var}} \rho_e = V \leq N$$

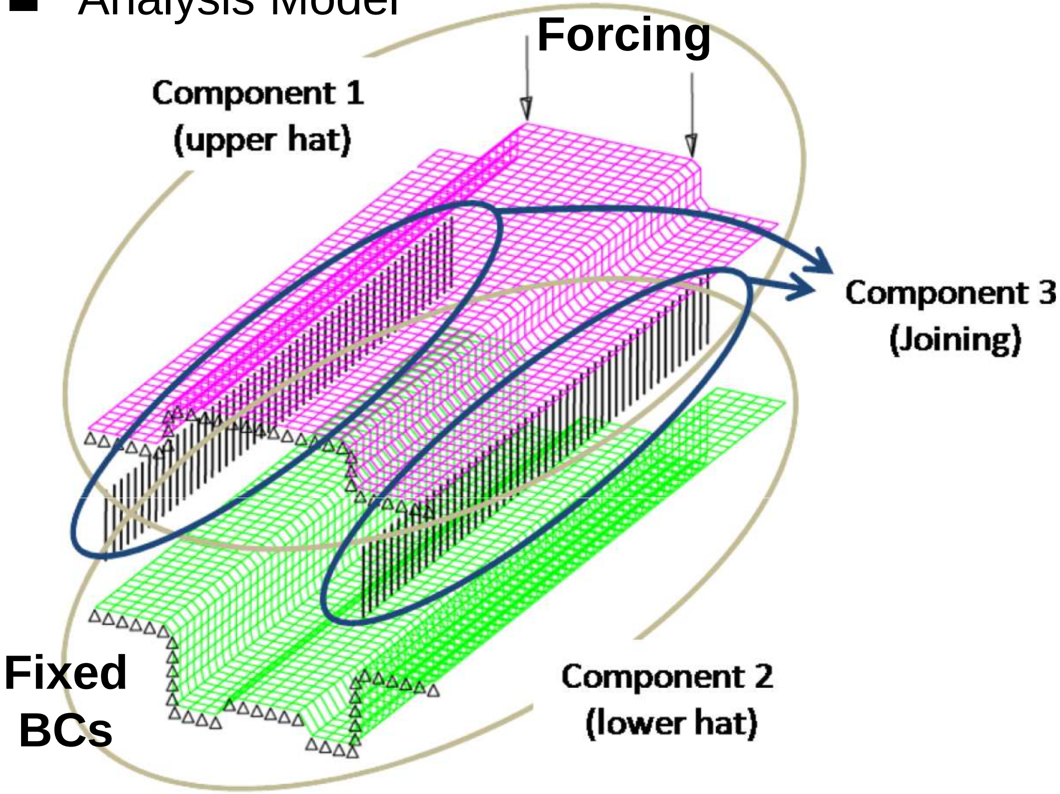
➢ Topology Optimizer

✓ MMA (Method of Moving Asymptote) – K. Svanberg ('87)

✓ MOC (Modified OC) – Z.-D. Ma, N. Kikuchi, I.Hagiwara ('93) Applicability both dynamic and static problems

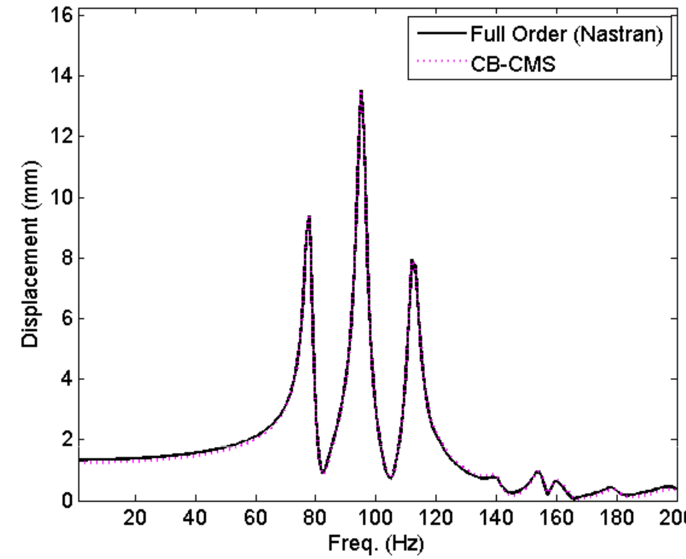
Structure used for numerical results

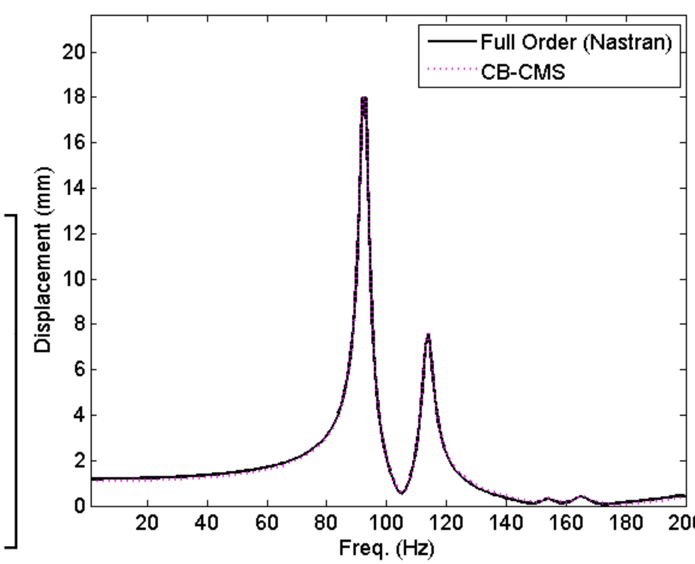
- Analysis Model



$$\begin{bmatrix} \mathbf{m}_u^{\mathrm{C}} & 0 & \mathbf{m}_u^{\mathrm{CN}} & 0 \\ 0 & \mathbf{m}_l^{\mathrm{C}} & 0 & \mathbf{m}_l^{\mathrm{CN}} \\ \mathbf{m}_u^{\mathrm{NC}} & 0 & \mathbf{m}_u^{\mathrm{N}} & 0 \\ 0 & \mathbf{m}_l^{\mathrm{NC}} & 0 & \mathbf{m}_l^{\mathrm{N}} \end{bmatrix} \quad \begin{bmatrix} \mathbf{k}_u^{\mathrm{C}} + \mathbf{k}_s^u & \mathbf{k}_s^{ul} & \mathbf{k}_l^{\mathrm{CN}} & 0 \\ \mathbf{k}_s^{lu} & \mathbf{k}_l^{\mathrm{C}} + \mathbf{k}_s^l & 0 & \mathbf{k}_u^{\mathrm{CN}} \\ \mathbf{k}_u^{\mathrm{NC}} & 0 & \mathbf{k}_u^{\mathrm{N}} & 0 \\ 0 & \mathbf{k}_l^{\mathrm{NC}} & 0 & \mathbf{k}_l^{\mathrm{N}} \end{bmatrix}$$

- ROM Validation





Optimization: static case

- Joining topology optimization for minimizing static compliance

$$\min_{\boldsymbol{\rho}} \quad c(\boldsymbol{\rho}) = \sum_{load=1}^{l_n} \mathbf{f^T U} = \sum_{\mathbf{load=1}}^{\mathbf{l_n}} \mathbf{U^T K_{st} U} \qquad \mathbf{K}_{st} = \mathbf{K}^0 + \mathop{\mathbf{A}}_{e=1}^{n_{var}} \rho_e^p \begin{bmatrix} \mathbf{k_s} & -\mathbf{k_s} \\ -\mathbf{k_s} & \mathbf{k_s} \end{bmatrix}$$

$$s.t.: \quad g(\boldsymbol{\rho}) = \sum_{e=1}^{n_{var}} \rho_e - N \leq 0\,; \quad 0 < \rho_{min} \leq \rho_e \leq 1$$

  - Fast evaluation via reduced order modeling for $\mathbf{K_{st} U = f}$

- **OC method (Bensøe and Kikuchi ,1988)**

Define Lagrangian → Stationary condition ← Design sensitivity

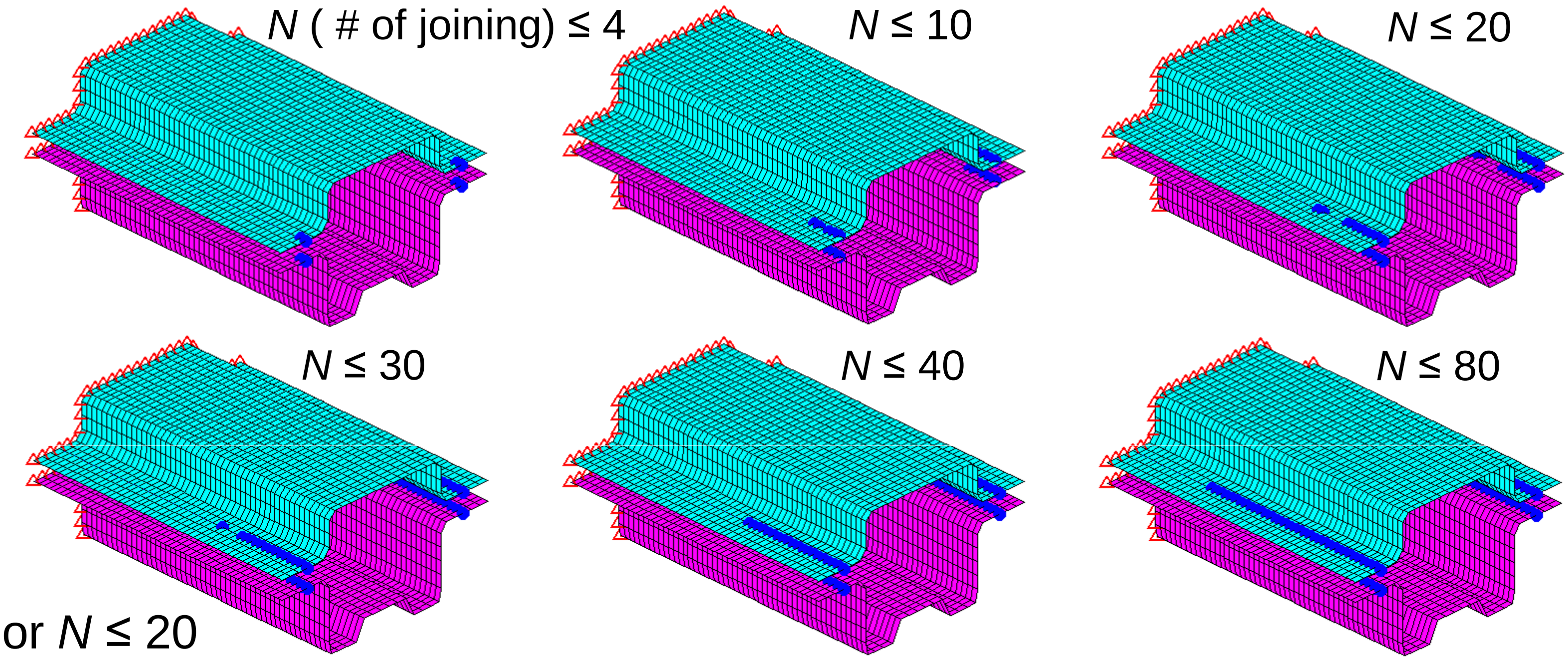
$$\mathcal{L} = c(\boldsymbol{\rho}) + \Lambda g(\boldsymbol{\rho}) \qquad B_K = -\Lambda_K^{-1} \frac{\partial c / \partial \rho_e}{\partial g / \partial \rho_e} \qquad \frac{\partial c(\boldsymbol{\rho})}{\partial \rho_e} = -p {\rho_e}^{p-1} \mathbf{u}_e^{\mathrm{T}} \mathbf{K}_s^0 \mathbf{u}_e$$

Update Rule

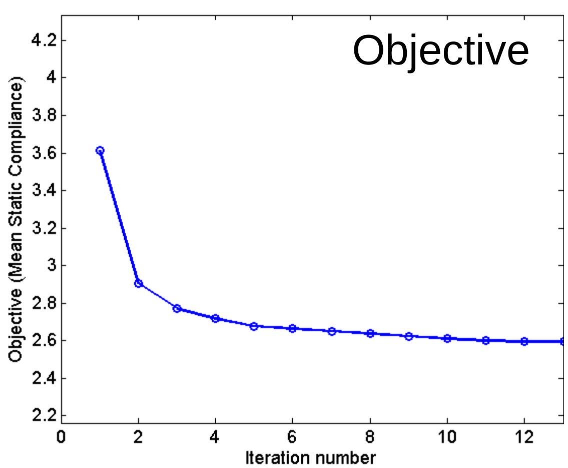
$$\rho_{K+1} = \begin{cases} \max\{(1-\zeta)\rho_K, \rho_{min}\} & \text{if} \quad \rho_K B_K^\eta \leq \max\{(1-\zeta)\rho_K, \rho_{min}\}, \\ \min\{(1+\zeta)\rho_K, 1\} & \text{if} \quad \min\{(1+\zeta)\rho_K, 1\} \leq \rho_K B_K^\eta, \\ \rho_K B_K^\eta & \text{otherwise.} \end{cases}$$

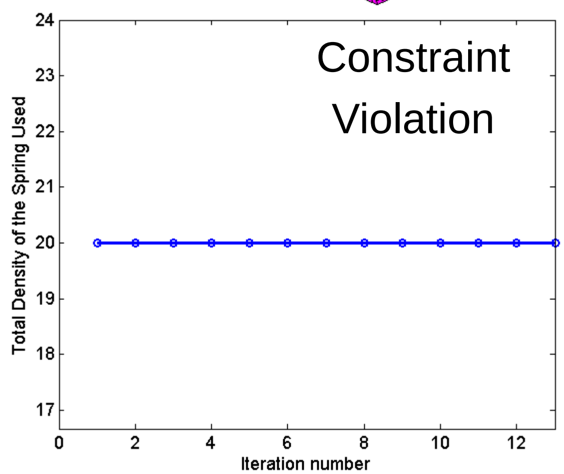
Optimization results: static case

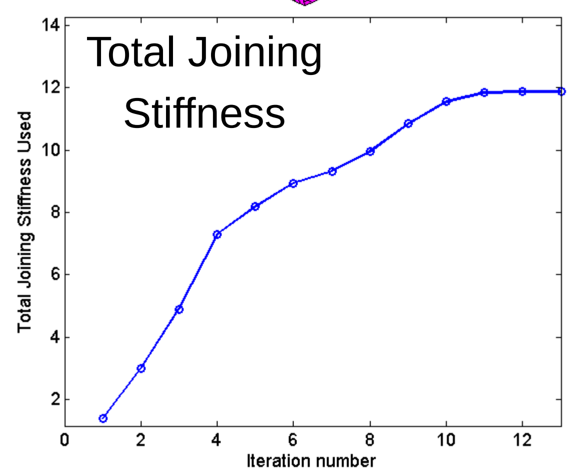
- Resulting Joining Topology



- For *N* ≤ 20







Optimization: dynamic case

- Joining topology optimization for minimizing dynamic compliance

$$\min_{\rho} \int_{f_{low}}^{f_{high}} \sum_{load=1}^{l_n} |\mathbf{f}^{\mathbf{T}}\mathbf{U}(\rho)|\mathbf{df} \qquad \mathbf{K}_{st} = \mathbf{K}^0 + \mathop{\mathbf{A}}_{e=1}^{n_{var}} \rho_e^p \begin{bmatrix} \mathbf{k_s} & -\mathbf{k_s} \\ -\mathbf{k_s} & \mathbf{k_s} \end{bmatrix}$$

$$s.t.: \quad g(\boldsymbol{\rho}) = \sum_{e=1}^{n_{var}} \rho_e - N \leq 0\,; \quad 0 < \rho_{min} \leq \rho_e \leq 1$$

  - ➢ Fast evaluation via reduced order modeling for $\mathbf{M\ddot{U}} + \mathbf{KU} = \mathbf{f_{ext}}$

- **Modified OC method (Ma, *et al*.,1992)**

Define Lagrangian → Stationary condition ← Design sensitivity

$$\mathcal{L} = (c(\boldsymbol{\rho}) - \mu g(\boldsymbol{\rho})) + (\Lambda + \mu) g(\boldsymbol{\rho}) = \tilde{c} + \tilde{\Lambda} g(\boldsymbol{\rho})$$

$$B_{K,MOC} = \tilde{\Lambda}_K^{-1} \left[\mu_K - \left(\frac{\partial c / \partial \rho_e}{\partial g / \partial \rho_e} \right) \right] \qquad \mu > \max_{e=1,n_{var}} \frac{\partial c / \partial \rho_e}{\partial g / \partial \rho_e}$$

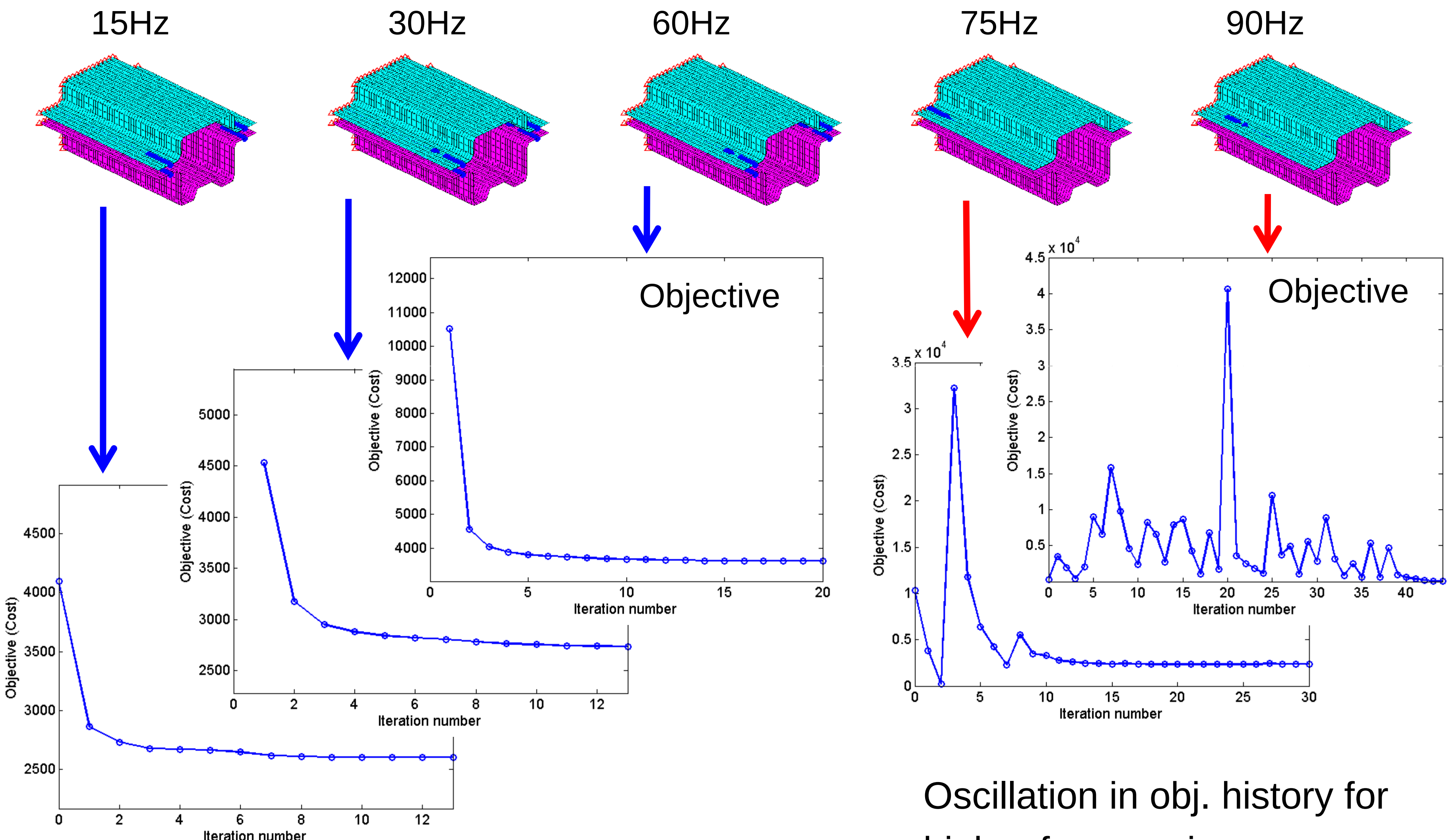
$$\frac{\partial c(\boldsymbol{\rho})}{\partial \rho_e} = -sgn(\mathbf{f}^T\mathbf{U}) p \rho_e^{p-1} \mathbf{u}_e^T \mathbf{K}_s^0 \mathbf{u}_e$$

Update Rule

$$\rho_{K+1} = \begin{cases} \max\{(1-\zeta)\rho_K, \rho_{min}\} & \text{if} \quad \rho_K B_K^{\eta} \leq \max\{(1-\zeta)\rho_K, \rho_{min}\}, \\ \min\{(1+\zeta)\rho_K, 1\} & \text{if} \quad \min\{(1+\zeta)\rho_K, 1\} \leq \rho_K B_K^{\eta}, \\ \rho_K B_K^{\eta} & \text{otherwise.} \end{cases}$$

Opt. results: single-freq. excitation

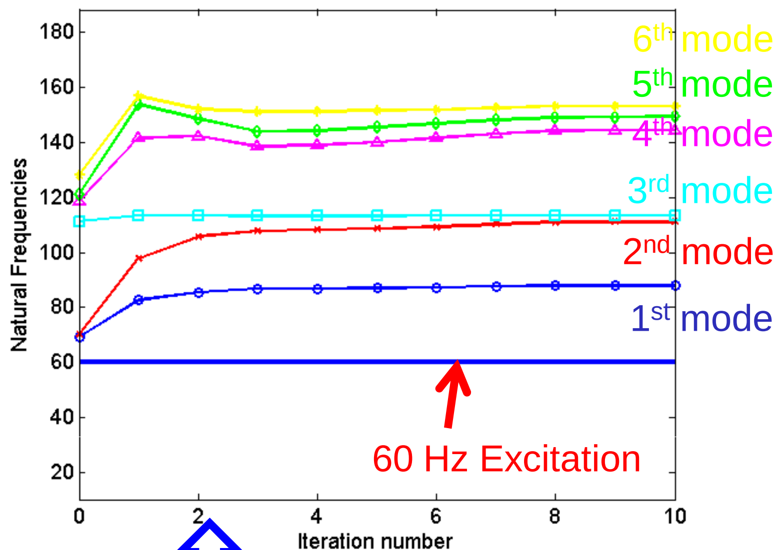
- Joining Topology for $N \leq 20$

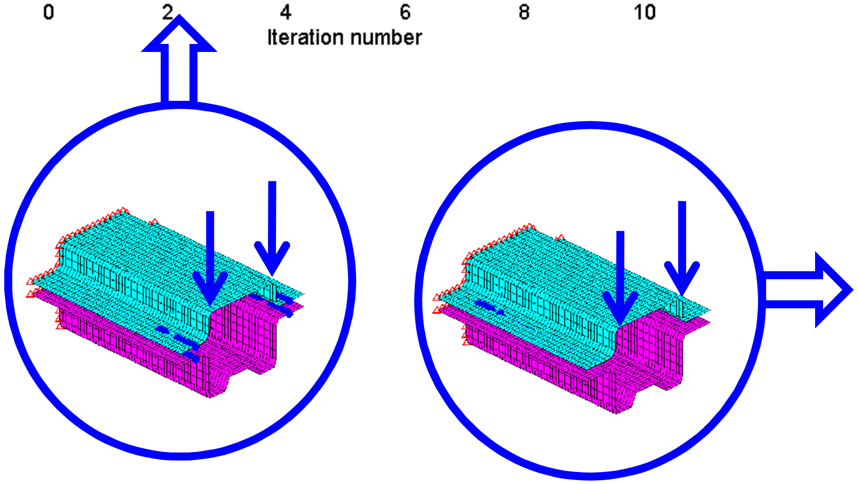


Oscillation in obj. history for higher frequencies

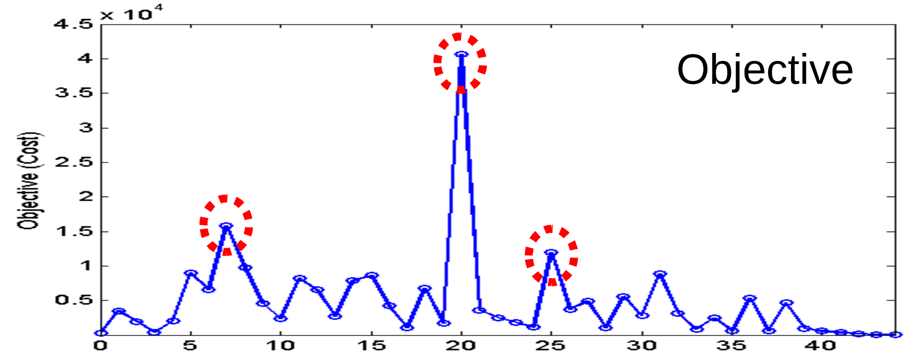
Natural freqs during optimization

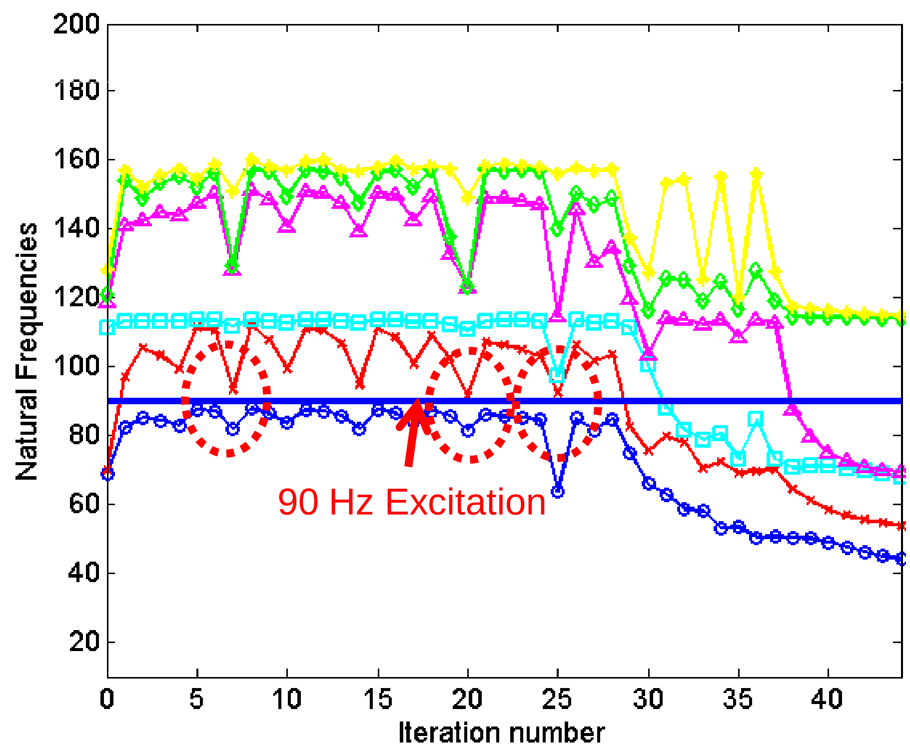
- Smooth Convergence Case (f_{ext} < 60 Hz)





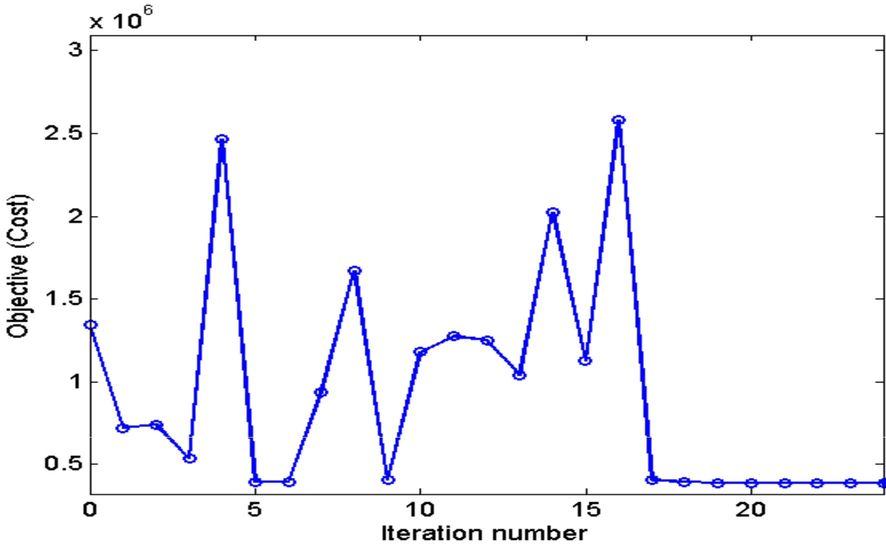
- Non-Smooth Case (f_{ext} ≥ 60 Hz)

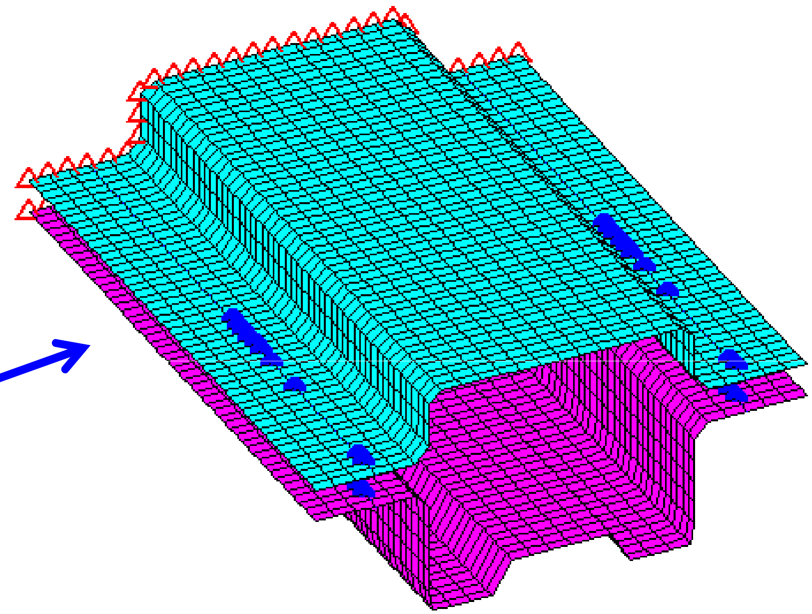




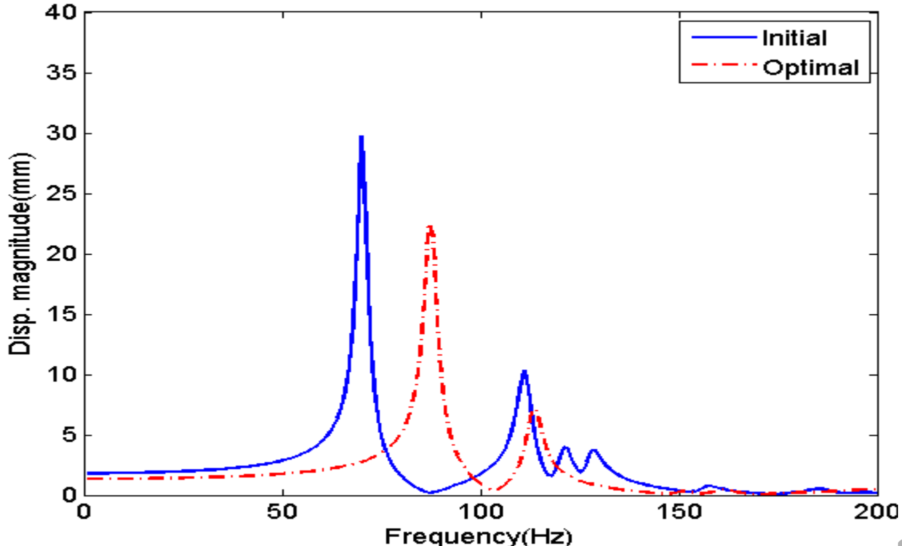
Opt. results: 50-100 Hz excitation

- Resulting topology and response





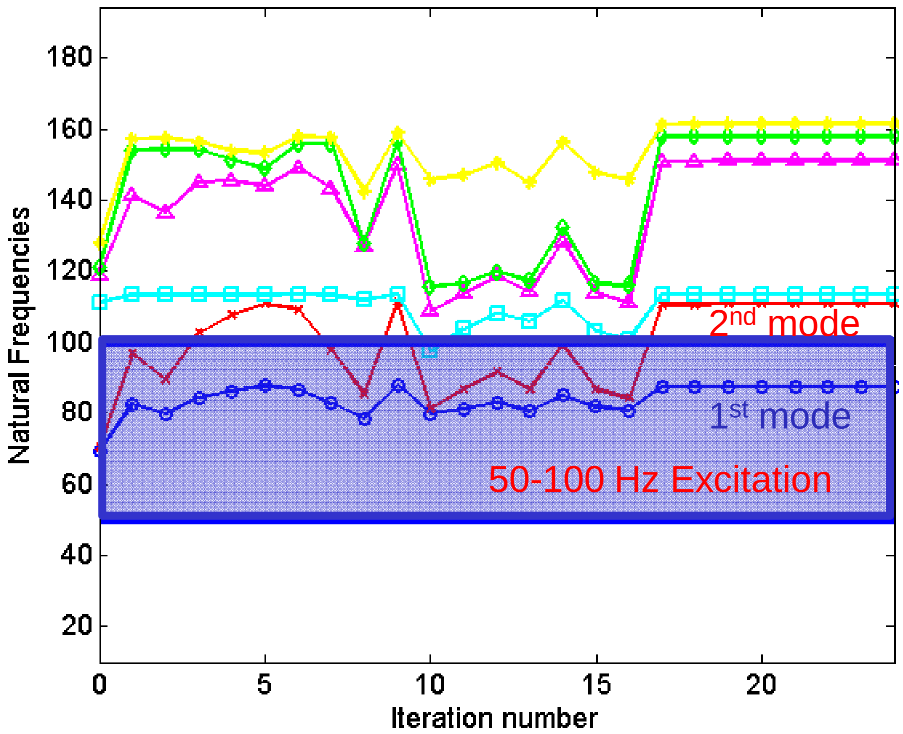
Final configuration



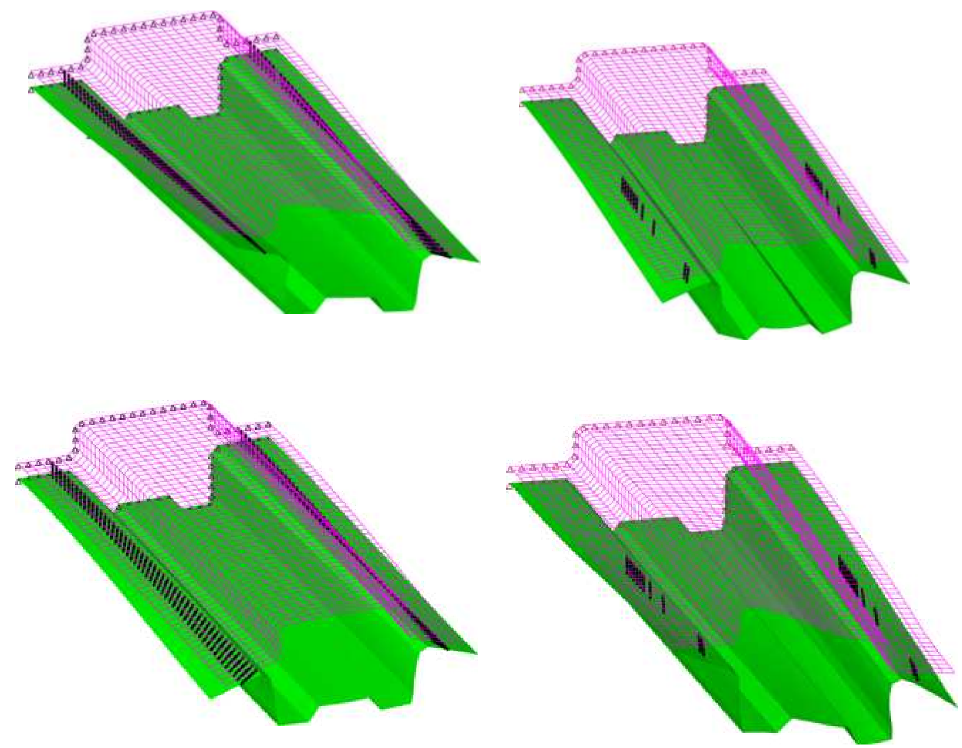
Initial configuration

Modes during optimization

- Natural frequencies during optimization



1^{st} mode | 1^{st} mode



2^{nd} mode | 2^{nd} mode

Initial configuration | **Final configuration**

Summary

- Component mode synthesis approach was used to:
  - Generate small ROMs for fast system-level analysis
  - Retain joining locations as physical DOF for design purposes
- Topology optimization was applied to joining design to achieve system-level structural performance targets
- Optimization results were obtained for a simple example structure
  - Static case
  - Dynamic case -- challenges noted for optimization for dynamic performance